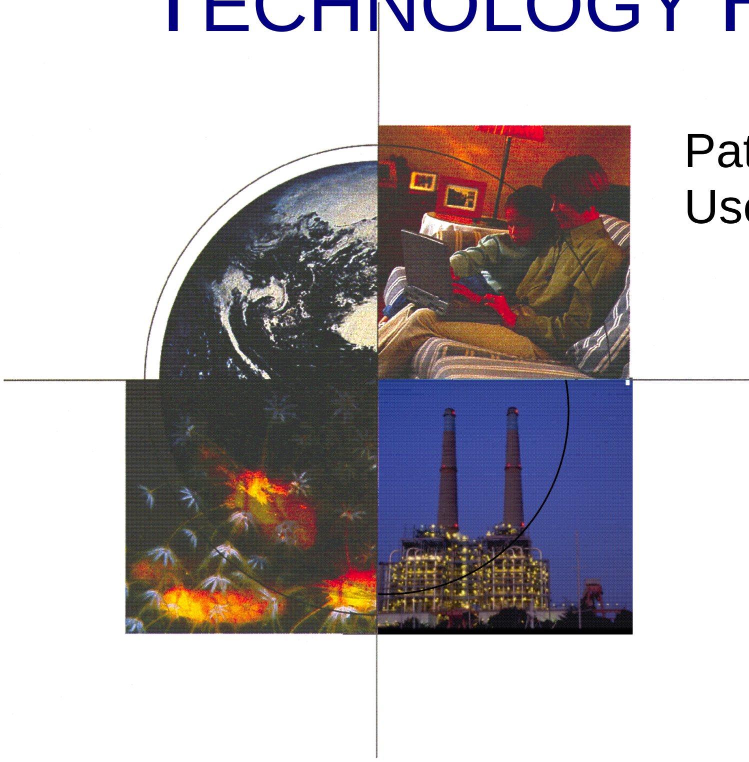
CARBON SEQUESTRATION TECHNOLOGY ROADMAP



Pathways to Sustainable Use of Fossil Energy

JANUARY 7, 2002

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

CARBON SEQUESTRATION TECHNOLOGY ROADMAP

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EXECUTIVE SUMMARY

> **Carbon Sequestration**
>
> - A third option for global climate change
> - Enables continued use of domestic energy resources and infrastructure
> - Potential for essentially unlimited storage capacity
> - Demonstrated industry interest, participation, and cost-sharing in public/private partnerships
>
> "We all believe technology offers great promise to significantly reduce [greenhouse gas] emissions -- especially carbon capture, storage and sequestration technologies."
>
> President George W. Bush
> June 11, 2001

Carbon sequestration has emerged as a third option for reducing greenhouse gas (GHG) emissions. Joining improved energy efficiency and the use of low-carbon fuels, carbon sequestration will enable the removal and permanent storage of carbon dioxide (CO_2) from fossil-energy systems. Carbon sequestration holds great potential to reduce GHG's at costs and impacts that are economically and environmentally acceptable. Other energy-related GHG's, such as methane and nitrous oxides, are important and are addressed as part of the U.S. Department of Energy's Carbon Sequestration Program. However, this roadmap only addresses CO_2.

Program Outcomes

In the near- and midterm, implementation of the roadmap can result in a reduction in the rate of growth of GHG emissions. In the long term, atmospheric stabilization of GHG concentrations can be achieved through implementation of all three options. The program's longer-term outcome directly supports the National Climate Change Technology Initiative (NCCTI) for atmospheric stabilization, as covered in a companion document, the NCCTI white paper, *CO_2 Capture and Storage in Geologic Formations* (draft).

The Carbon Sequestration program has conducted analyses to quantify the benefits that the United States could realize from an investment in these research and development pathways. The program developed a "Pathway to Stabilization" scenario in which the *growth* in GHG emissions is slowed in the near term and eventually stopped at the 2010 reference case level. By working with market growth and natural capital stock turnover, such a strategy allows time for new technology and low-cost options. It also prevents a rapid increase in GHG emissions over the next 20 years thus minimizing the need for steep, economically disruptive reductions in the future.

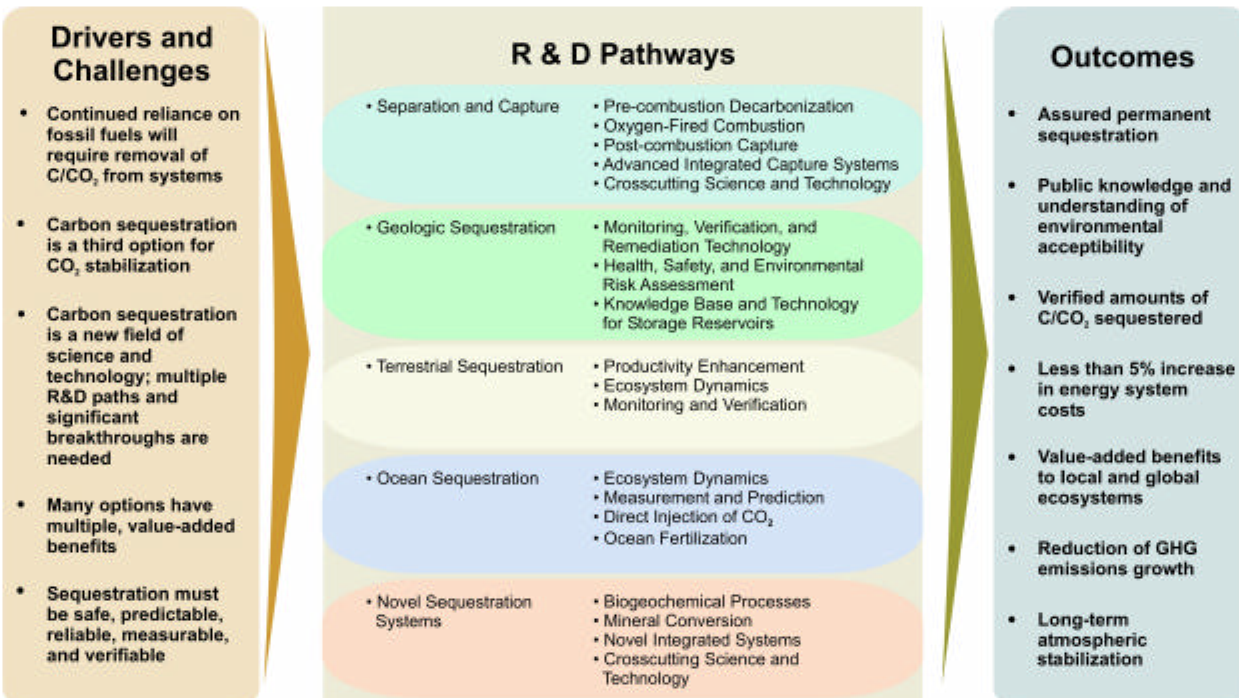
Public-Private Partnerships

The effort to develop carbon sequestration technology involves extensive public-private partnerships among government, industry, academia, non-government organizations, and the public at large. Many of these partnerships are international in scope, and include the International Energy Agency's Greenhouse Gas Research and Development Programme (IEA/GHG), the European Commission, international science organizations, and individual countries. Domestic partners include industry, DOE Office of Science, National Science Foundation, scientific and academic communities, non-governmental environmental organizations, and regional, state, and local organizations. This collaborative approach supports the NCCTI objectives of providing market-based options that build on science and technology innovations.

The Roadmap Today and Tomorrow

The carbon sequestration technology roadmap defines the major drivers and challenges, R&D pathways, and desired outcomes that have been identified. It represents a general consensus to date on *what* major science and technology pathways have potential for achieving the goals of carbon sequestration. The implementation of these pathways—*how* the work will be accomplished—will be carried out by various stakeholders.

The roadmap has five major pathways: separation and capture; geologic, terrestrial, and ocean sequestration; and novel sequestration systems. The roadmap will evolve as more information becomes available from ongoing policy analysis and technology planning efforts. To date, an extraordinary amount of progress has already taken place.



The Path Forward

This technology roadmapping effort represents an ongoing exchange of information among policy makers, scientists, technology developers, regulators, and the public. It is based on ideas, data, and perspectives developed by a broad range of stakeholders over the past several years. The goal of these efforts is to develop a *consensus* view on the key science and technology needs and opportunities. As in any new area of science and technology, there is still significant uncertainty. Areas of disagreement may exist over what paths to follow—and how to follow them. As the knowledge base improves, some pathways may not be viable due to environmental, economic, technical, or other reasons. Given that carbon sequestration is basically in its infancy in terms of science and technology, discoveries may open new pathways. Through a continuing process of roadmap development, the R&D opportunities that can turn possibilities into realities will be identified.

CARBON SEQUESTRATION TECHNOLOGY ROADMAP

I. Introduction

The term "carbon sequestration" refers to the removal of carbon dioxide (CO_2) from either man-made emissions or the atmosphere and the safe, essentially permanent storage of CO_2 or other carbon compounds. Alternatively, the CO_2 can be converted to value-added products. There are two main types of sequestration: *direct* sequestration, where CO_2 is removed from energy systems, and *indirect* sequestration, where CO_2 is removed from the ambient atmosphere by enhanced natural processes. Sequestration is one of three options for stabilizing CO_2 concentrations in the atmosphere. Until the late 1990s, carbon sequestration was not yet in the scientific lexicon. It is less familiar to the public at large than the other two options for reducing greenhouse gases—improved efficiency and the use of low-carbon fuels.

A. Vision and Goals

The vision for carbon sequestration is to possess the scientific understanding and develop those technology options that ensure environmentally acceptable approaches, thus reducing man-made emissions and overall atmospheric concentrations of CO_2. There are two major goals that support this vision.

- Demonstrate environmental acceptability to the public.
- Achieve sequestration with less than a 5% increase in energy system costs.

Supporting objectives are to assure essentially permanent storage, verify the amount of carbon or CO_2 sequestered, and provide value-added benefits to local and global economies and ecosystems.

This roadmap primarily addresses the near- and midterm outcome of reduced growth rate of CO_2 emissions. In direct support of the NCCTI, the expected long-term outcome is to help attain atmospheric stabilization of CO_2 concentrations. The technology and global partnership opportunities for long-term stabilization through sequestration are presented in the draft NCCTI white paper *CO_2 Capture and Storage in Geologic Formations* as well as the companion white papers on ocean and terrestrial sequestration *Ocean Carbon Sequestration White Paper* and *Terrestrial Carbon Sequestration White Paper*, both released on October 12, 2001. The roadmap is a "living" tool; it will be modified to reflect program results and new technology opportunities. In particular, options for long-term stabilization will increase as knowledge is gained.

B. Public-Private Partnerships

Public-private collaboration in research planning and execution is a cornerstone of the Carbon Sequestration Program. This is particularly important given strong industry interest both domestically and internationally. From the Department of Energy's perspective, 1997 represented the start of the Office of Fossil Energy's (FE) formal carbon-sequestration efforts, with initial funding of the FE Carbon Sequestration Program and a seminal white paper prepared by the Massachusetts Institute of Technology. Two years later, the Office of Fossil Energy and

Office of Science released a joint report, *Carbon Sequestration: State of the Science*, which defined five major pathways for sequestration. Since then, FE has worked with international and domestic stakeholders in a series of collaborative efforts.

The individual pathways may be pursued by different stakeholders. In addition to the FE Carbon Sequestration Program, other organizations, public and private, are currently or may in the future work on these and other new pathways. Many areas of collaborative R&D are being planned and performed today. This is consistent with the general consensus of the scientific community—that there are near- and midterm actions to be taken as we work to gain better understanding of the long-term opportunities.

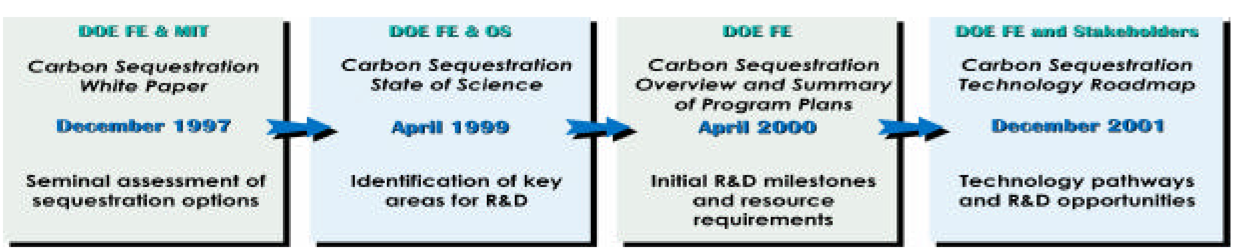
C. The Path Forward

The roadmapping activity is an iterative process. At a given point in time, the roadmap will provide a snapshot of our current knowledge and understanding. Ongoing collaboration will serve two purposes:

- Refining the technology roadmap to reflect new opportunities for *what* technology pathways should be explored, and
- Supporting the ongoing, iterative process of program planning and analysis on *how* the Carbon Sequestration Program interacts with other implementing organizations (industry, IEA/GHG, the international research community, the academic community, the DOE Office of Science, and others) in pursuing various pathways.

"Progress through Partnership," the theme of the First National Conference on Carbon Sequestration, May 2001, guides the roadmap's evolution. There are differing political, regulatory, and economic perspectives in the global climate change issue. Nonetheless, the prevailing consensus is that significant, positive actions are to be taken in the near term as longer-term pathways and solutions emerge. The NCCTI, for example, clearly recognizes the role and importance of carbon sequestration as an effective option for stabilizing atmospheric concentrations of CO_2, using market-based solutions employing innovative technology.

The roadmap will be a "living" document, with the framework and details evolving as new data, information, and opportunities are defined. In coming years, further outreach activities and expert workshops will be conducted as part of this continuing process. This will include, for example, establishing regional Sequestration Networks to focus on diverse regional needs and opportunities. As significant changes in our understanding of carbon sequestration emerge, the roadmap will be revised accordingly.



Roadmap Evolution

II. Pathways to Stabilization

A. The Three Options

The challenge of global climate change is to decouple GHG emissions and the use of low-cost, reliable energy resources. Two options have generally been considered for this. The first is to conserve energy and to use it more efficiently. The second is to switch to renewables, nuclear power, and low-carbon fuels such as hydrogen or natural gas. A third option is carbon sequestration, which removes CO_2 from energy systems and stores it.

B. Stabilization Scenarios

The Carbon Sequestration Program has conducted analyses to quantify the benefits that the United States could realize from an investment in carbon sequestration research and development as a means of working toward the longer-term strategy of stabilizing atmospheric concentrations of greenhouse gases. Figure 1 shows a "Pathway to Stabilization" scenario in which the growth in greenhouse gas emissions is slowed over the next 20 years and eventually stopped at the reference case 2010 level. This scenario is but one of many which could be envisioned. By working with growth and natural capital stock turnover, the pathway to stabilization allows time for new technology and low-cost options. It also prevents a rapid increase in GHG emissions over the next 20 years thus reducing any need for steep, economically disruptive reductions in the future.

Figure 1. Greenhouse Gas Emissions Scenarios for the United States

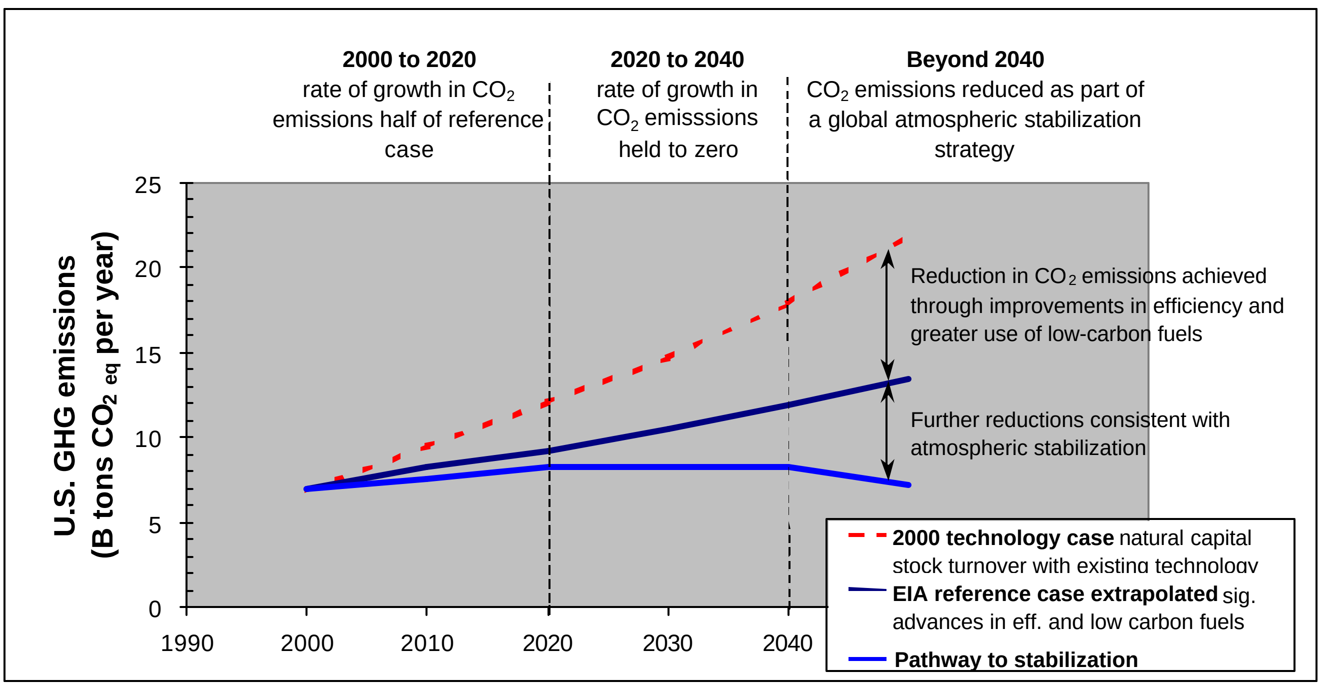


Figure 1 compares the Pathway to Stabilization scenario to a business as usual scenario for U.S. GHG emissions. The middle line is the reference case projection from the Energy Information Administration's Annual Energy Outlook 2001, extrapolated to 2050. Note that the reference case is fairly aggressive relative to technology development and assumes a decrease in carbon intensity of one percent per year. If such improvements in carbon intensity are not achieved, the need for other GHG emissions reduction options will be greater.

Based on the magnitude of emissions reduction needed under the pathway for stabilization, the capacity of geologic formations is large enough to store many decades or centuries worth of emissions, as shown in Table 1. These capacity estimates are considered to be conservatively low. CO_2 sequestration potential in geologic reservoirs depends on a variety of factors. These include the reservoir volume, porosity, permeability, and pressure. Because these factors vary widely even within the same reservoirs, it is difficult to determine the storage potential in these reservoirs with certainty. For example, the storage potential in saline reservoirs has been estimated to range from 5-500 Giga Tons (Gt) of CO_2 in the U.S. and 320 to 10,000 Gt globally. However, more detailed analysis of the Mt. Simon Sandstone reservoir in the Midwestern U.S. by Battelle has shown that the storage capacity in this formation alone may range from 115 to 655 Gt. Within the Mt. Simon Sandstone itself the storage capacity varies widely due to local differences in geologic parameters.

Table 1. CO_2 Storage Capacities of Domestic Geologic Formations

Geologic Reservoir	Estimated CO_2 Storage Capacity (Billions of tons CO_2)
Unmineable Coal Beds	15-20
Depleting Oil Reservoirs	40-50
Depleting Gas Reservoirs	80-100
Saline Formations	5-500
High Organic Shales	TBD
TOTAL	140-670
Source: ARI; Bergman et al.	

Over the next 20-30 years, value-added sequestration applications (those which both reduce greenhouse gas emissions and result in additional production of oil and gas) can provide a cost-effective means of reducing emissions and provide collateral benefits in terms of increased domestic production of oil and gas. In the mid- and long term, advanced CO_2 capture technology and integrated CO_2 capture, storage, and conversion systems can provide cost-effective options for deep reductions in GHG emissions.

C. Other Greenhouse Gases

In addition to CO_2, methane (CH_4) and nitrous oxide (N_2O) are the other major anthropogenic emissions that contribute to global climate change. On a molecular basis, both CH_4 and N_2O are more potent greenhouse gases than CO_2. However, in terms of emissions quantity, CO_2 far outstrips the others and is thus the primary focus of mitigation efforts. Control of CH_4 and N_2O is considered in the analysis of "multi-gas" impacts and mitigation potential. Efforts to capture and store non-CO_2 GHGs are included in the Sequestration Program but are not covered in this roadmap. It is recognized that CO_2 capture and storage systems must not exacerbate the contributions from other GHG emissions.

III. Research and Development Pathways

The Carbon Sequestration Program is pursuing five Technology Pathways:

- Separation and capture
- Geologic sequestration
- Terrestrial sequestration
- Ocean sequestration, and
- Novel sequestration systems.

These five pathways encompass a broad set of opportunities, both in terms of technology and national and global partnerships. Figure 2 provides an overview of the issues, status, approach, and synergies associated with each. The Carbon Sequestration Program is implementing R&D appropriate to the state of the science. The specific research thrusts being pursued within each pathway are described in subsequent sections.

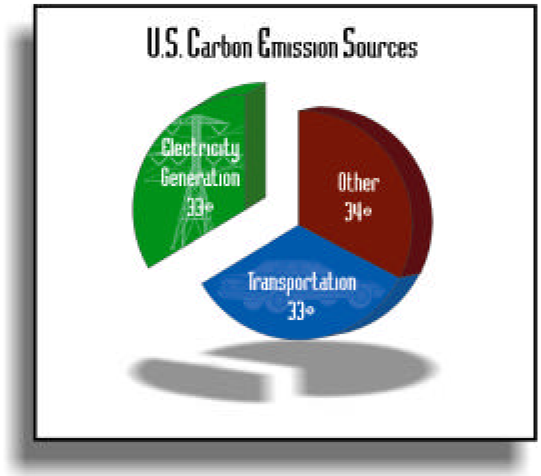
Several important issues crosscut many of the pathways and will be addressed during technology development. Examples of crosscut issues are transportation of CO_2 from source to sequestration site, systems to measure and verify the amount of carbon sequestered, and public acceptance of deployments. Such crosscut issues are included in the detailed pathway discussions, where appropriate.

Figure 2. Carbon Sequestration Roadmap

PATHWAY	KEY ISSUES	STATUS	APPROACH	PROGRAM SYNERGIES
Separation and Capture	• High capital and operating cost • Reduced efficiencies	• Current cost at 30-50 $/ton CO_2 from an existing coal-fired power plant • Up to 35% reduction in net power production due to efficiency losses	• Develop: – Improved conventional technology – Advanced capture technology – Processes that concentrate CO_2 during fuel conversion	• Vision 21 • Innovations for Existing Plants • Global Partnerships
Geologic	• Public awareness and recognition of the value of large-scale storage of CO_2 • Environmental acceptability and storage verification & monitoring	• 30MM tons per year CO_2 used in the U.S. for EOR, 7MM from man-made point sources • Significant number of natural CO_2 storage analogs exist • Experience with large-scale injection of CO_2 into underground formations: – Significant with oil reservoirs – Much less with gas reservoirs and coal seams – Limited with saline formations, (Statoil has been injecting 1 MM tons of CO_2 per year into the Sleipner saline formation since 1996)	• Expand technology base for value-added applications for CO_2 • Address public concerns by obtaining field experience with CO_2 storage – Develop increased understanding of natural analogs – Develop methods and technologies for tracking CO_2 migration underground and verifying storage integrity – Develop best practices for CO_2 injection that lead to stable storage	• EOR, EGR • DOE-OS • USGS • Global Partnerships
Terrestrial	• Idealogical resistance to terrestrial sequestration to offset emissions versus emissions reduction • Cost-effective methods for monitoring & verifying (M&V) carbon in terrestrial ecosystems	• Utilities and other entities engaged in numerous forestation and reforestation/enhancement activities in anticipation of tradeable credits • Promising M&V technologies exist, but are not adequately proven for acceptability and scalability (esp. soil carbon)	• Demonstrate the multiple benefits associated with terrestrial sequestration, particularly on disturbed lands • Verify new technology for monitoring and verification of carbon in terrestrial ecosystems	• Innovations for Existing Plants • DOE-OS • USDA/USFS • OSM • Global Partnerships
Ocean	• Environmental aspects of increased carbon storage in the ocean unknown • Public concerns over future health of oceans	• Inadequate scientific understanding of the ocean carbon cycle. • Data to determine ecological and environmental parameters not available	• Collaborate with DOE-OS, NSF, and international entities to conduct exploratory scientific research • Investigate CO_2 hydrates formation and stability related to CO_2 storage	• Global Partnerships • EGR (Hydrates) • DOE-OS • NSF
Novel Sequestration Systems	• CO_2 conversion not economic: – slow reactions – large energy requirements	• No economical applications of CO_2 conversion identified to date; concepts are at the exploratory research stage	• Conduct exploratory research to discover new biological and chemical CO_2 conversion processes	• Innovations for Existing Plants • Advanced Research • DOE-OS • NSF

Acronym Key: DOE-OS (Department of Energy - Office of Science), EGR (Enhanced Gas Recovery), EOR (Enhanced Oil Recovery), NSF (National Science Foundation), OSM (Office of Surface Mining), USDA (United States Department of Agriculture), USFS (US Forest Service), USGS (US Geologic Survey).

A. Separation and Capture



CO_2 separation and capture is the first step of direct sequestration and entails capturing CO_2 from power plants, industrial processes, fuels manufacturing, and other energy systems before it is emitted to the atmosphere. While some technology exists to perform this today, the key barrier is cost. Using currently available technology at electricity generation plants, separation and capture would increase energy costs by 50% or more. Research and development is aimed at developing capture systems with the following characteristics:

- Low capital cost,
- Low parasitic load,
- High percent reduction in emissions, and
- Integration with NO_x, SO_x, $PM_{2.5}$, and Hg pollutant control systems

Roughly one-third of the United States' anthropogenic CO_2 emissions come from power plants. Because most fossil fuel conversion systems are based on air-fired combustion, the bulk of the flue gas is nitrogen (air is 79% nitrogen), making it difficult to concentrate and capture CO_2. Concentrated CO_2 (greater than 90%) is needed for most storage, conversion, or reuse applications. Sequestration R&D seeks to overcome this barrier and develop capture systems that produce a highly pure, pressurized stream of CO_2 at relatively low cost.

There are two primary goals: 1) reduce CO_2 capture costs for existing plants by 75%; and 2) reduce CO_2 capture costs from new plants by 90%. Figure 3 shows the separation and capture roadmap. There are five major research thrusts.

- **Pre-Combustion Decarbonization**
- **Oxygen-Fired Combustion**
- **Post-Combustion CO_2 Capture**
- **Advanced Integrated Capture Systems**
- **Crosscutting Science and Technology**

These pathways address needs for both current and potential fossil fuel conversion systems. This includes retrofit of the existing capital stock of air-fired combustion and industrial processes, the repowering of existing assets, and the deployment of new plants for fuels, power, heat, and other products. R&D pathways associated with CO_2 capture were originally identified in an industry-led workshop co-funded by BP Amoco, the IEA Greenhouse Gas R&D Programme, and the U.S. Department of Energy held in September 1999. Collaborative work continues with both domestic and global partners.

Figure 3. Separation and Capture

Research Thrust	Barriers and Issues	Technology Opportunity	Technology Targets*	Outcomes *
Pre-Combustion Decarbonization Capture CO_2 from the decarbonization process	• Existing capture technologies operate at too low a temperature. Syngas must be cooled down and often reheated, increasing cost and reducing efficiency • Often more economic to combust sygnas before full shift, reducing the portion of CO_2 captured	• Chemical sorbents • Physical sorbents • CO_2-selective membranes • Hybrid sorbent/membrane systems • Membranes that both shift CO and separate CO_2/H_2 • Gas/liquid contactors	• Establish pilot-scale test capability • 2005 Complete pilot-plant testing of one or more promising technologies • 2006 Initiate cost-shared precommercial test of a pre-combustion decarbonization system with advanced CO_2 capture	• Efficient, low-cost electricity and hydrogen production from fossil fuels with low GHG emissions • Commercially viable options for retrofit/ repower of existing fossil fuel conversion systems to reduce emissions of CO_2 per unit of power or other products by 80% or more
Oxygen-Fired Combustion Burn fuels in enriched air or pure oxygen to produce a concentrated stream of CO_2	• Oxygen from cryogenic air separation is expensive, and oxygen combustion consumes 4.5 times more oxygen than gasification • Combustion of fuels in pure oxygen occurs at a temperature too high for existing boiler or turbine materials. CO_2 recycle to control temperature increases parasitic load	• O_2-selective membranes • Advanced cooling cycles • Compact boilers and turbines that can operate at high temperature and pressure	• 2003 Establish pilot-scale test capability • 2002 Complete studies of advanced boiler designs for oxygen-enriched air firing • 2005 Complete pilot-scale testing of one or more promising technologies • 2006 Initiate cost-shared precommercial-scale test of an advanced oxyfuel concept	
Post-Combustion Capture Capture CO_2 from the flue gas of an air combustion system	• CO_2 is dilute in flue gas, requiring large gas handling systems • Non-CO_2 flue gas components (e.g. oxygen, acid gases, particulate matter) adversely affect available separation technologies	• Chemical sorbents • Physical sorbents • CO_2-selective membranes • Hybrid sorbent/membrane systems • Gas/liquid contactors	• 2003 Establish pilot-scale test capability • 2005 Complete pilot-scale testing of one or more promising technologies • 2005 Complete proof-of-concept testing of three or more promising technologies • 2008 Cost-shared power plant retrofit with advanced CO_2 capture technology • 2006 Initiate cost-shared commercial-scale power plant testing	
Advanced Integrated Capture	• Limited number of promising approaches identified • Lack of experimental data	• Chemical looping	• 2005 Laboratory-scale testing of one or more promising advanced concepts	• New concepts to broaden scope of cost-effective CO_2 capture
Crosscutting Science and Technology Enable synergistic advances between CO_2 control and other systems	• Available CO_2 capture technologies exhibit poor selectivity and/or cause significant loss of temperature and pressure • Decreased efficiency and resulting increase in resource consumption disapproved by NGOs and others	• Heat and pressure integration with other system components. • Integration/combination with NO_x, SO_2, Hg and particulate matter emissions control • Hybrid oxyfuel/post combustion capture systems • Coordination of R&D efforts with related international activities	• 2006, 2008, 2010 Respectively provide enabling science and technology base for the above pathways • 2006 Develop analysis and modeling capabilities to enable optimization of integrated systems	• Complete integration of CO_2 capture into advanced fossil fuel conversion systems

*The portfolio of activities in the capture and separation area are aimed at two overarching goals: 1) by 2008 demonstrate 90% reduction in the cost of CO_2 capture for new builds, and 2) by 2010 demonstrate 75% reduction on the cost of CO_2 capture for retrofit applications. The overall cost reduction goals include both equipment cost and parasitic load.

B. Geologic Sequestration

Geological sequestration is a form of direct sequestration, where CO_2 is stored in underground formations. Certain of these underground formations have structure, seals, porosity, and other geologic properties that make them ideal for long-term storage of CO_2. Most of these formations have stored crude oil, natural gas, brine, and CO_2 for millions of years. Geologic formations are likely to be the first large-scale options to be considered for CO_2 storage, since developers of geologic storage technologies can draw on the experience gained from oil, gas, coal, and water-resource management. Geologic sequestration also has cost advantages because many power and industrial plants are located near suitable geologic sites.

In some cases, injection of CO_2 into a geologic formation is a "value-added" process because it can enhance the recovery of oil, which can help offset the costs of CO_2 capture. Currently, in the United States, 30 million tons of CO_2 are injected into geologic formations each year as part of enhanced oil recovery. Research and development is underway in this area to expand the number and type of formations amenable to "value-added" storage of CO_2.

Development of a broad range of geologic sequestration options has numerous benefits. Storage of CO_2 in saline formations has the benefit of being in close proximity to many large point sources of CO_2 emissions. Storage of CO_2 in depleted gas reservoirs will enable operators to utilize existing infrastructure for injecting CO_2. Storage of CO_2 in oil reservoirs and unmineable coal seams may lead to increased oil and coalbed methane recovery.

There are four primary goals for research in this area: (1) develop reliable monitoring, verification and mitigation technology for geologic formations; (2) demonstrate the environmental acceptability of underground storage in diverse geologic settings; (3) understand the behavior and assure the predictability of CO_2 in geologic storage; and, (4) develop field practices that lower the cost of storage and ensure formation integrity.

Figure 4 sets forth the three major research thrusts of the geologic sequestration roadmap:

- **Monitoring, Verification, and Mitigation Technology**
- **Health, Safety, and Environmental (HSE) Risk Assessment**
- **Knowledge Base and Technology for CO_2 Storage Reservoirs**

The roadmap on geologic sequestration builds on input obtained from several sources. These include: (1) a carbon sequestration workshop co-funded by BP, the IEA Greenhouse Gas R&D Programme (GHG), and DOE in September 1999; (2) a series of international R&D efforts for developing geologic storage technology including NASCENT (Europe), GEODISC (Australia), and RECOPOL (EU/Poland); and, (3) most recently, the Carbon Capture Project workshop (funded by DOE, the European Union, Norway and a consortium of private companies) in Potsdam, Germany, entitled "Building the SMV Family of Technology Providers" that set forth storage, monitoring, and verification (SMV) technology needs.

Figure 4. Geologic Sequestration

RESEARCH THRUST	ISSUES AND BARRIERS	TECHNOLOGY OPPORTUNITIES	TECHNOLOGY TARGETS	OUTCOMES
1. Monitoring, Verification and Mitigation Technology				
Monitoring and Verification Technology	• Monitoring and verification of CO_2 storage with monitor wells is costly • Time-lapse seismic approaches cannot detect concentrations of CO_2 • Inadequate understanding of equilibria between multi-component gases, oil, and water	• Tracers that can be reliably monitored from the subsurface and surface • High resolution seismic and non-seismic methods for identifying concentration of CO_2 • Development of low-cost, near-surface technology for presence of CO_2 • Subsurface and near-surface geologic models of storage areas • Migration and flow modeling of CO_2 in storage reservoir, underlying aquifer, and overlying sediment.	• Affordable indirect monitoring technology acceptable to permitting agency by 2006 • Low-cost, direct CO_2 monitoring technology acceptable to permitting agency by 2008 • Reservoir monitoring field test, with modeling plus indirect and direct detection by 2010	• Reliable monitoring and verification technology builds confidence in operation of geologic storage
Mitigation Technology	• Mitigation technology for CO_2 leakage not currently available	• Intelligent, self-activating control systems • Coupled subsurface, land surface, and atmospheric models of CO_2 migration and dispersion	• Coupled flow and dispersion models by 2008 • Field tested CO_2 leakage mitigation technology by 2012	• Real-time mitigation technology reduces risks of geologic storage
RESEARCH THRUST	ISSUES AND BARRIERS	TECHNOLOGY OPPORTUNITIES	TECHNOLOGY TARGETS	OUTCOMES
2. Health, Safety and Environmental Risk Assessment				
Data and Methodology	• HSE risk assessment methodology for geologic storage does not exist • Database for HSE risk assessment is lacking • Natural seismic events with effects on storage integrity are difficult to anticipate	• Adaptation of risk assessment methodology from natural gas storage and oilfield waste injection to geologic storage of CO_2 • Define performance standards for geologic storage of CO_2 • Identify safe and acceptable CO_2 leakage rates appropriate to each geologic setting	• HSE risk assessment methodology for geologic storage acceptable to permitting agency by 2004 • National and regional HSE databases by 2006	• Risks of geologic storage of CO_2 are well understood
Natural and Operating Analogs	• Lack of long-term data on interactions of CO_2 and storage reservoirs • No data on stress related changes to integrity of caprock and reservoir • Limited experience with CO_2 storage field operations	• Comprehensive studies of natural CO_2 reservoirs and gas storage fields • Integrated studies of natural seepage of CO_2 with reservoir simulation and basin modeling • Safe, cost-effective CO_2 storage field development and operating practices	• "Best practices" development and operations manual by 2004 • Comprehensive study of natural CO_2 fields by 2005 • Geomechanical studies of gas storage fields by 2006 • Integrated natural CO_2 seepage and modeling studies by 2007	• Public confidence with geologic storage is greatly enhanced

RESEARCH THRUST	ISSUES AND BARRIERS	TECHNOLOGY OPPORTUNITIES	TECHNOLOGY TARGETS	OUTCOMES
3. Knowledge Base and Technology for CO_2 Storage Reservoirs				
Depleted and Near-Depleted Oil and Natural Gas Reservoirs	• Conflicts between optimizing recovery of oil and maximizing long-term storage of CO_2 • Reluctance of industry to consider storage of CO_2 in depleted gas reservoirs • Long-term effects of CO_2 on reservoir properties not well understood • Natural seepage of gases from reservoirs not quantified	• Studies of long-term CO_2 flow and migration in hydrodynamic formations • Modeling and testing for maximizing long-term storage of CO_2 with enhanced oil and gas recovery • Geochemical research of effects of CO_2 on caprock integrity and reservoir properties • Geomechanical research on effects of stress on reservoir seal integrity • Geologic database on caprock and overlying strata	• Field demos of CO_2 storage in oil reservoirs by 2005 • Geologic and reservoir properties database by 2006 • Validated geochemical and geomechanical models by 2007 • Feasibility of CO_2 storage and enhanced gas recovery by 2008	• Technology in place for use of oil and gas reservoirs for long-term storage of CO_2 with incremental production of oil and natural gas
Deep Coal Seams	• CO_2/N_2 flow and storage in coals not well defined • Uncertain effects of CO_2 on coal reservoir permeability • Competition from using N_2 rather than CO_2 for ECBM • Lack of criteria for identifying favorable coal formations	• Laboratory tests and reservoir modeling studies of injection of CO_2/N_2 mixtures • Laboratory and modeling studies of swelling behavior in domestic coals • Alternative injection well configurations and procedures for maximizing CO_2 injection • Screening criteria and models for matching coal storage sites with CO_2 sources	• Validated models of CO_2 storage in deep coal reservoirs by 2003 • Effects of CO_2 on major coal types by 2004 • Site selection criteria and screening models by 2005 • Field demos of maximum CO_2 storage in coal seams by 2008	• Coal seams established as feasible CO_2 storage reservoir with incremental production of natural gas
Saline Aquifers	• Limited data on reservoir properties and capacity • Lack of data on CO_2 vertical and lateral migration • Inadequate data on solubility and mineral trapping in brine systems • Limited field experience	• National geologic and reservoir properties databases for saline aquifers • CO_2 flow modeling for diverse aquifer flow settings • Laboratory studies of CO_2 in diverse brine-chemical-mineral systems • Horizontal and multi-lateral wells for improved injectivity of CO_2	• CO_2/fluid interactive studies by 2004 • Verified geochemical and flow models by 2005 • National database by 2006 • Field demos of aquifer storage by 2010	• Large, regionally diverse geologic storage capacity becomes available
Novel Storage Reservoirs	• Limited understanding of feasibility and storage capacity of other potential storage reservoirs (e.g., gas shales, below basalt)	• Identify, characterize and test novel geologic settings for CO_2 storage and "value-added" hydrocarbon production	• Establish feasibility and capacity of organically rich gas shale reservoirs and other geologic storage options by 2008	• Additional CO_2 storage options become available
Crosscutting Research and Technology	• Data on long-term cement and well completion integrity is lacking • Unreliable data on location and integrity of abandoned wells • Long-term corrosion effects	• Research on long-term cement integrity • National database of abandoned oil and gas wells • Low-cost, reliable well abandonment technology • Corrosion control and materials science research	• Alternative well cementing materials and procedures by 2006 • Database and technology on well abandonment by 2007 • Economically feasible corrosion resistant materials and mitigation procedures by 2010	• Integrity and safety of CO_2 transportation, injection, and storage is improved

C. Terrestrial Sequestration

In the process of photosynthesis, plants absorb CO_2 and release oxygen. The carbon from the CO_2 is biochemically transformed into sugar compounds necessary for plant growth and structure. Most of the carbon eventually cycles back to the atmosphere through decomposition, but a fraction is deposited in wetland sediments and soils. Through indirect sequestration, anthropogenic carbon emissions can be partially offset by increasing the amount of carbon stored in the terrestrial ecosystem.

Vegetation and soils are widely recognized as carbon storage sinks. The global biosphere absorbs roughly 2 billion tons of carbon annually, an amount equal to roughly one-third of all global anthropogenic carbon emissions. However, significant amounts of carbon are also contained in both the roots and in the soil. The inventory of carbon stored in the global ecosystem equals roughly 1,000 years worth of annual absorption, or 2,000 Gt of carbon.

In the near term, sequestration of carbon in terrestrial ecosystems offers a low-cost means of reducing net carbon emissions with significant collateral benefits: restored habitat for plants and wildlife, reduced runoff, and increased domestic production of agriculture and forest products. Terrestrial carbon sequestration could serve a strategic role in offsetting carbon emissions from vehicles and other dispersed energy systems, such as residential heating and small industrial processes. The goal of the terrestrial sequestration pathway is to integrate carbon sequestration in vegetation and soils with fossil fuel production and use, such that there are economically competitive and environmentally safe options for offsetting a portion of the nation's CO_2 emissions. Figure 5 presents the terrestrial sequestration roadmap. There are three major research thrusts.

- **Productivity Enhancement**
- **Ecosystem Dynamics**
- **Monitoring and Verification**

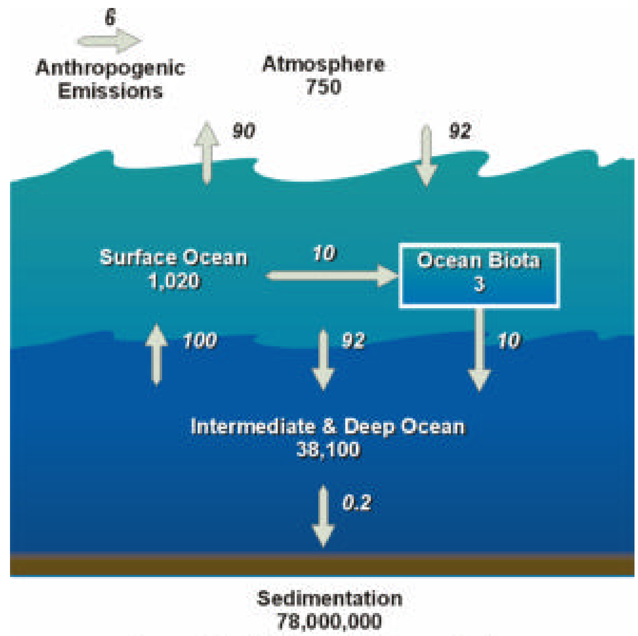
The roadmap is coordinated with a range of stakeholders. These include, for example, the U.S. Forest Service of the Department of Agriculture, environmental non-governmental organizations, state and local organizations, the Office of Surface Mining of the Department of Interior, and the DOE Office of Science.

Figure 5. Terrestrial Sequestration

Research Thrust	Barriers and Issues	Technology Opportunities	Technology Targets	Outcomes
Productivity Enhancement Provide multiple benefits through enhancement of unproductive and disturbed lands	• Idealogical resistance to terrestrial sequestration to offset emissions versus emissions reduction • Integrating sequestration with other land use goals and practices • Regional-specific variations in land use regulation and practice, mining practices, and ecosystems	• Integration of fossil energy byproduct use with land reclamation and productivity improvement • Forestation and reforestation/enhancement activities by utilities and other entities in anticipation of tradeable credits	• 2003: Assess domestic opportunities in mined-land reclamation • 2005: Initiate field testing in representative regional terrestrial ecosystems • 2007: Demonstrate the multiple benefits associated with terrestrial sequestration, particularly on disturbed lands.	• Enhanced carbon storage capacity • Restoration of land to higher-value uses • Regional improvements in ecosystem stability, biodiversity, and water quality
Ecosystem Dynamics Determine relationships between sequestration practices and ecosystem response	• Interactions and impacts on water quality and availability • Impacts on long-term ecosystem stability	• Assessment of potential synergies between sequestration and water quality improvement • Assessment of sequestration practices on measures of ecosystem health (e.g., biodiversity, resistance to stress)	• Determine carbon balance and long-term carbon capacity in regional terrestrial ecosystems • Assess ecosystem response to different sequestration practices	• Assurance of carbon sequestration as an effective tool for climate change mitigation while assuring environmental quality
Monitoring and Verification Provide accepted technologies and protocols to assess carbon flux	• Cost-effective methods for monitoring & verifying (M&V) are not available for carbon in terrestrial ecosystems • Promising M&V technologies exist, but are not adequately proven for acceptability and scalability (esp. soil carbon)	• Remote sensing and non-intrusive measurement systems • Data mining and analysis to support models as surrogates to direct measurement	• 2003: Verify capability of new technology for monitoring and verification of carbon in terrestrial ecosystems. • 2006: Field test of remote systems to demonstrate cost-effectiveness	• Cost-effective, broadly accepted protocols and tools available to (1) assure and measure net CO_2 uptake and (2) support market-based trading systems

D. Ocean Sequestration

The oceans contain carbon in the form of dissolved CO_2, plant and animal matter, and mineral carbonates (shells). The amount of carbon stored in the oceans is enormous; 38,000 billion metric tons compared to 2,000 billion tons in terrestrial ecosystems. However, little is understood about the deep ocean ecosystem and R&D efforts in the area of ocean sequestration are being pursued with caution. Because of their enormous size, the oceans remain an important long term carbon sequestration option. Pathways for ocean sequestration include direct sequestration, in the form of CO_2 injection into the oceans, and indirect sequestration through the enhancement of the ocean's CO_2 uptake from the atmosphere.



Reservoirs - billions of tonnes of carbon
Fluxes - bilions of tonnes of carbon per year
Source: "Atmospheric Carbon Dioxide and the Ocean," Siegenthaler and Sarmiento, *Nature* volume 365, pp 119-125.

Recognizing the need for basic research, ocean sequestration R&D is a collaborative effort of the Office of Fossil Energy and the Office of Science, NSF, and international scientific communities. The purpose of the FE effort is to help establish the applied science and technology base to integrate fossil energy systems with ocean sequestration when and if it proves to be a viable option. There are two major goals.

- Improve the understanding of the ocean carbon cycle and deep ocean ecosystems.
- Improve the understanding of the environmental effects of actions aimed at increasing the amount of CO_2 stored in the ocean.

Figure 6 presents the ocean sequestration roadmap. There are four major research thrusts:

- **Ecosystem dynamics**
- **Measurement and prediction**
- **Direct injection of CO_2**
- **Ocean fertilization**

Continued development of the ocean sequestration pathway will be a collaborative effort involving a broad range of national and international expertise. Recent inputs include the results of a jointly sponsored experts' workshop hosted by the American Society of Limnology and Oceanography on the scientific and policy uncertainties surrounding the use of ocean fertilization; a direct ocean sequestration experts' workshop hosted by DOE and the Monterey Bay Aquarium Research Institute; and the draft NCCTI *Ocean Carbon Sequestration White Paper*, as well as activities of the National Science Foundation (NSF).

Figure 6. Ocean Sequestration

Research Thrust	Barriers and Issues	Science and Technology Opportunities	Technology Targets	Outcomes
Ecosystem Dynamics Determine ecosystem response to carbon sequestration	• Environmental impacts of increased carbon storage in the ocean unknown	• Improved data on ecological, hydrodynamic, and other environmental factors • CO_2 tolerance and physiological response of ocean biota	• Identify and assess potential perturbations from sequestration processes	• Assurance of ecosystem protection and stability
Measurement and Prediction Determine carbon cycle impacts	• Inadequate scientific understanding of the ocean carbon cycle • Unknown impacts on long-term carbon fluxes	• Biogeochemical and physical mechanisms of carbon transport and transformation • Long-term fate of additional CO_2 uptake	• Develop fundamental understanding and assure the predictability of CO_2 fate	• Assurance of net increase in ocean uptake of CO_2
Direct Injection of CO_2 Introduce concentrated CO_2 streams into deep ocean waters	• Unknown behavior of dense CO_2 streams at various pressure and depth conditions • Unknown impacts on ocean ecosystems	• Formation of CO_2 hydrates as stable form of storage • CO_2 plume dynamics	• Establish the scientific knowledge base needed to assess the environmental and technologic acceptability of this option. • Investigate CO_2 hydrates formation and stability related to CO_2 storage	• Determination of pathway viability and longterm sequestration stability
Ocean Fertilization Use macro-nutrients (e.g., iron) to stimulate phytoplankton growth	• Net carbon storage as yet unconfirmed • Long-term response to fertilization not known • Unknown impacts on ocean ecosystems	• Major planned scientific research led by NSF, DOE-OS, and the international ocean sciences communities	• Establish the scientific knowledge base needed to assess the environmental and technologic acceptability of this option • Assessment of long-term CO_2 fate and flux	• Determination of pathway viability and longterm sequestration stability

E. Novel Sequestration Systems

An alternative to storing CO_2 is to convert it into fuels, other useful products, or benign solids. Numerous CO_2 conversion phenomena are found in nature. The most common is photosynthesis, but there are others: mollusks use CO_2 dissolved in ocean water to build their shells, sandstone reacts with CO_2 in the air to form minerals, and evidence suggests that CO_2 trapped in geologic formations over eons has been converted to methane, carbonates and other species through biogeochemical processes that are not fully understood. In developing CO_2 conversion processes, the pathways seek to mimic naturally occurring phenomena. This is a challenging task; CO_2 is a highly stable compound containing a very low amount of chemical energy, and the natural conversion processes are slow and inefficient as a result.

Although the technology barriers in the area of CO_2 conversion and reuse are high, the potential payoff is large. Technology breakthroughs could lead to regenerable carbon-based energy systems or permanent, benign carbon storage. Such capabilities will be needed to achieve atmospheric stabilization over the long term. There are two primary goals in this area:

- Improve the speed and energy efficiency of CO_2 conversion processes.
- Identify conversion processes that produce high-value by-products to improve process economics.

Figure 7 presents the novel sequestration systems roadmap. There are four major research thrusts.

- **Biogeochemical Processes**
- **Mineral Conversion**
- **Novel Integrated Systems**
- **Crosscutting Science and Technology**

This pathway is coordinated with the DOE Office of Science, NSF, the IEA/GHG, and other national and international science organizations. Efforts will focus on identifying paths of potential high payoff in the long term and engaging a diverse set of researchers to identify new research ideas and multi-disciplinary approaches.

Figure 7. Novel Sequestration Systems

Research Thrust	Barriers and Issues	Technology Opportunities	Technology Targets	Outcomes
Biogeochemical Processes Convert CO_2 to fuels (CH_4, H_2, others) and chemicals	• CO_2 conversion not economic: – slow reactions – large energy requirements • No economical applications of CO_2 conversion identified to date; concepts are at the exploratory research stage.	• Identify microbiology/ biogeochemistry pathways and reactions occurring in nature • Determine specific mechanisms and enzyme systems • Enhance the kinetics of pathways to commercially useful rate	• Conduct exploratory research to discover new biological and chemical CO_2 conversion processes • Develop selected processes to obtain performance competitive with conventional fuels and chemical production	• Natural-analog processes that convert CO_2 to value-added products • Closed-loop fossil-based systems that close the carbon cycle
Mineral Conversion Convert CO_2 to minerals, the most stable carbon compounds	• Slow reaction rates • Energy intensive reactions • Uses for high volumes of solids products are unknown now	• Identify and develop reaction pathways with favorable energetics • Reduce heat and pressure inputs • Simplify conversion reaction vessels	• Orders of magnitude improvements in reaction rates and energy needs • Identify large-scale marketable uses	• Storage or reuse of converted solid mineral products (stable carbon forms that can be permanent) considered
Novel Integrated Systems Novel processes integrating sequestration across the fossil energy production, conversion, and use cycle	• New ideas and concepts with potential are needed • Revolutionary rather than evolutionary ideas are needed	• "Clean sheet" approaches to system design that incorporate sequestration capability into new systems	• Stimulate recognition of potential and related interest in the research community • Establish process to improve yield (number and quality) of new ideas	• Low-cost fossil energy systems with integrated sequestration for sustainable use of coal, oil, and gas
Crosscutting Science and Technology Enable interdisciplinary advances for novel systems	• Fundamental science research needed to elucidate potential pathways • Lack of interdisciplinary approaches hinders radical approaches	• Microbiology • Geochemistry • Biocatalysis • Genomics • Biomimetic and other new chemistry	• Improved understanding of natural processes and means of adapting this knowledge.	• Broader options for sequestration processes and systems

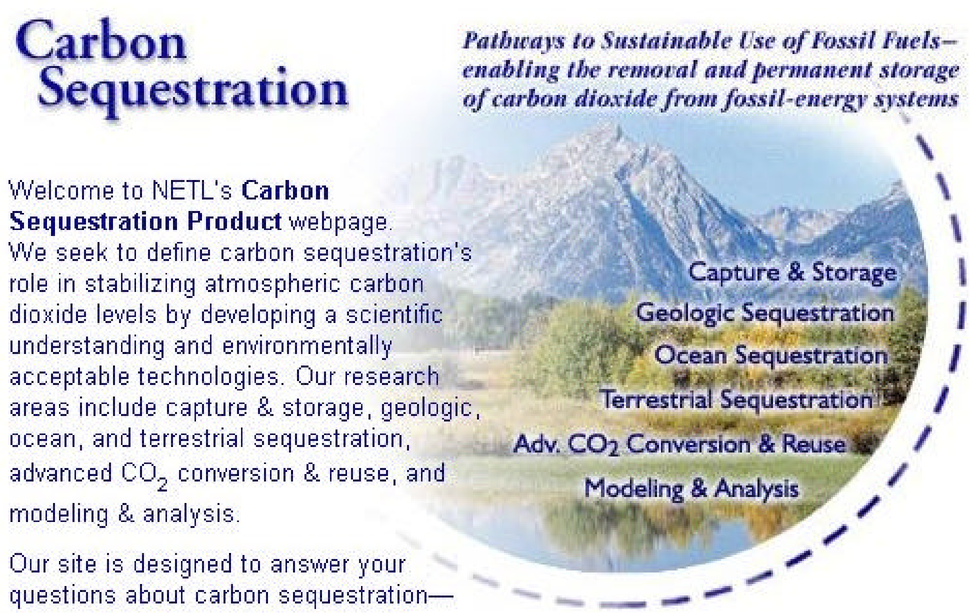
IV. Outreach and Communications

Effective outreach and communication is an essential component of a program that builds domestic and international partnerships. To facilitate this process, the Carbon Sequestration Program will focus on a series of outreach efforts.

- Supporting regional activities to identify and assess CO_2 source-transportation-sequestration opportunities.
- Working with environmental non-governmental organizations to further define efforts required to assure environmental acceptability.
- Assessing critical crosscutting issues such as measurement and verification of the amounts of carbon sequestered.
- Exploring novel concepts that may lead to entirely new pathways, particularly in the area of conversion and reuse.
- Continuing public outreach activity to provide information and educational materials about carbon sequestration as a third option.

As we move forward, some pathways may not be viable due to environmental, economic, technical, or other reasons. Given that the carbon sequestration is basically in its infancy in terms of science and technology, we may expect discoveries that will open new pathways. Through the process of roadmap development, the R&D opportunities that can turn possibilities into realities will be identified.

For more information, or to sign up for our monthly electronic Carbon Sequestration Newsletter, please visit our web page: http://www.netl.doe.gov/products/sequestration.



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For more information on the Carbon Sequestration Program please visit our web site:

NETL Carbon Sequestration Page @
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